

Heavy-Ion Physics at the LHC

This document¹ is to be presented at the Town Meeting at Brookhaven National Laboratory, Jan. 21-23, 2001, and made available to NSAC to aid in the long range planning process.

¹On Dec. 20, 2000, a group of interested people met at LBNL to examine the possibility and prospects of US participation in heavy-ion experiments at the LHC. The conclusions, incorporating considerable input from the community at large, are presented in this white paper.

1. Why should the US actively participate in the LHC heavy-ion physics program?

In 2006, the Large Hadron Collider (LHC) at CERN will be the highest energy accelerator operating on Earth. Its approved experimental program includes a strong heavy-ion collision component, with one dedicated heavy-ion experiment, ALICE, and an additional heavy-ion program in CMS. LHC data from heavy-ion collisions at unprecedentedly high energies will thus begin to complement the Relativistic Heavy Ion Collider (RHIC) scientific program shortly after 2006. Even a moderate US participation in the LHC heavy-ion experiments will have a significant impact on the LHC program. At the same time, this will lead to a very positive feedback on the understanding of RHIC physics and dynamics.

The center of mass energy for heavy-ion collisions at the LHC will exceed that at RHIC by a factor of about 30. This provides exciting opportunities for addressing unique physics issues in a completely new energy domain:

- LHC-energy heavy-ion collisions provide a unique opportunity to study the properties and dynamics of QCD in the classical regime. The density of the low x virtual gluons in the initial state will be high enough for saturation to set in so that their subsequent time evolution is governed by classical chromodynamics.
- Due to the higher incident energy compared to RHIC, semihard and hard processes will be a dominant feature at the LHC and gross properties of the collision can be reliably calculated using perturbative QCD.
- Very hard strongly interacting probes, whose attenuation can be used to study the early classical chromodynamic and thermalization stages of the collision, are produced at sufficiently high rates for detailed measurements.
- Weakly interacting probes, such as direct photons, W^\pm and Z^0 bosons produced in hard processes, will provide information about nuclear parton distributions at very high Q^2 . The impact parameter dependence of their production is sensitive to the spatial dependence of shadowing and saturation effects.
- Compared to RHIC, the ratio of the lifetime of the quark-gluon plasma state to the time for thermalization is expected to be larger by an order of magnitude so that parton dynamics will dominate the fireball expansion and the collective features of the hadronic final state.

A complete picture of heavy-ion collision dynamics at high energies requires the analysis of the complementary information gained at both RHIC and the LHC. US participation in both programs is essential for securing a stable place at the frontier of heavy-ion research for our scientific community.

2. New opportunities for heavy-ion physics at the LHC

2.1 General conditions of heavy-ion collisions at the LHC

The center of mass energy for collisions of the heaviest ions at the LHC will exceed that available at RHIC by a factor of about 30. This opens up a new physics domain with exciting opportunities. Historical experience suggests that such a large jump in available energy usually leads to new discoveries. Whereas the SPS has produced excited strongly interacting matter near the conditions for quark deconfinement [1], the goal of the heavy-ion experimental programs at RHIC and the LHC is to investigate the quark-gluon plasma in full detail. RHIC is the first machine that allows deep penetration into this new phase, creating quark-gluon plasmas which are sufficiently long-lived to make them accessible to a variety of specific experimental probes. A comprehensive experimental program addressing this exciting physics, which foresees a broad range of systematic studies and future upgrades to both the machine and the detectors, has been put into place and will dominate the US effort in this field for the coming decade.

Heavy-ion collisions at the even higher LHC energy, on the other hand, will explore regions of energy and particle density which are significantly beyond those reachable at RHIC. At LHC energies, the bulk of particle production will be due to collisions between low- x virtual gluons in the incoming nuclei. The colliding nuclei before impact may be described as densely packed “gluon walls” approaching each other at the speed of light. The phase-space density of low momentum gluons is saturated and gluon merging becomes important [2, 3, 4]. As a result the gluon density is sharply reduced compared to low-density perturbative expectations, limiting in a self-consistent way the growth of the production cross section for low- p_T minijets. This qualitatively new regime of “gluon saturation” at low x and large A becomes accessible for the first time with heavy ions in the LHC. In Pb+Pb collisions at the LHC, the p_T -scale at which gluon saturation sets in is estimated to be around 2 GeV [5]. At this scale, perturbative QCD is likely to be applicable. For the first time the bulk of transverse energy and particle production as well as the initial conditions for the subsequent expansion of the hot matter formed in the reaction zone can thus be reliably calculated within perturbative QCD.

While the concept of a dense wall of virtual gluons in the incoming nuclei can be probed in eA collisions [6], in AA collisions it plays a decisive role in our thinking about the production of dense strongly interacting matter and its subsequent evolution into a thermalized quark-gluon plasma. When two nuclei collide, the phase coherence among their virtual partonic constituents is broken and these partons come on shell. Due to the large number of gluons in any given low- p_T quantum state this process may be described by classical chromodynamics. Theoretical methods based on such classical concepts (Weizsäcker-Williams fields [3], classical Yang-Mills dynamics [7], etc.) have been developed in recent years and can be experimentally tested at the LHC. Classical Yang-Mills fields are known to exhibit chaotic evolution, and this may be an important mechanism for early thermalization of the particles produced during the initial stage of the collision [7].

The energy density of the thermalized matter created at the LHC is estimated to be 20 times higher than can be reached at RHIC, implying an initial temperature T_0 which is greater by more than a factor of 2 [8]. Due to the higher initial parton density, thermalization also happens more rapidly, and the ratio of the quark-gluon plasma lifetime (i.e. the time until the first hadrons begin to form) to the thermalization time accordingly increases by a factor 10. As a result, the fireballs created in heavy-ion collisions at the LHC spend nearly their entire lifetime in a purely partonic state, widening the time window available for experimentally probing the quark-gluon plasma state.

Studies of the quark-gluon plasma can be done efficiently by using “hard probes” [9], e.g. high- p_T jets or photons, heavy quarkonia, and W^\pm or Z^0 mesons. The “hard scale” characterizing these probes is the squared momentum transfer, Q^2 , necessary for their production. At the high collision energies provided by the LHC, the cross sections for very high $Q^2 > (50 \text{ GeV})^2$ processes are large enough to comfortably allow detailed experimental studies. The hard probes are created at very short times, $\tau_{\text{hard}} \sim 1/Q \leq 0.01 \text{ fm}/c$, and their production can be calculated perturbatively once the nuclear structure functions are known. This time is early enough to probe the classical chromodynamic stage of the collision during which the “gluon walls” decay. The bulk of the secondary matter materializes somewhat later, at $\tau_0 \sim 1/T_0 \sim 0.2 \text{ fm}/c$. The hard probes are embedded in this secondary matter and explore its properties by scattering off it on their way out. The time available for this “probing” is of the order of $5 - 10 \text{ fm}/c$, given by the lifetime of the hot QGP state or the time needed for the probe to travel through the reaction zone, whichever is shorter. The medium dependence of these scattering processes can be calculated theoretically [10, 11, 12] so that the properties of the medium can be inferred from the measured final state of the hard probe.

2.2 Unique physics questions and specific probes at the LHC

The high energy scale of the LHC makes heavy-ion collisions sensitive to the nuclear parton distributions, $f_A(x, Q^2)$, at very low x , $x \sim 10^{-3}$. High parton densities leading to partonic overlap, gluon recombination and saturation are generally expected for sufficiently small values of x and/or Q^2 and large mass numbers A . In Pb+Pb collisions at the LHC, gluon saturation strongly affects the production of secondary partons with $p_T < 2 \text{ GeV}$. Different probes can be used to explore the consequences of gluon recombination and saturation on the nuclear structure functions, i.e. on the distribution of virtual quarks, antiquarks and gluons in the *pre-collision* wave function of the incoming nuclei, and to study their effect on the density and further evolution of the *post-collision* environment.

In order to probe the *pre-collision* state of the nuclei and to measure the initial nuclear wave function, one can study the production of direct photons, W^\pm and Z^0 vector bosons (observed through their leptonic decay channels), and the yields of open charm and beauty mesons. Direct photons are sensitive to the quark and gluon distributions whereas the vector bosons probe mostly the quark and anti-quark

distributions. Open charm and beauty production measures properties of the gluon distribution function. W^\pm and Z^0 production can be studied in pp collisions at RHIC, but in AA collisions the RHIC energy is too low for an accurate measurement. A high-statistics study of W^\pm and Z^0 vector bosons in AA collisions would thus be unique to the LHC [13].

The probes mentioned previously can be used to measure shadowing, i.e. the modification of the free nucleon parton distributions by the nuclear medium. In addition to the unmodified structure functions, accessible in ep and pp collisions, and the homogeneous shadowing, which can be studied in eA , pA and AA collisions, AA collisions also allow the investigation of the spatial dependence of shadowing in the plane transverse to the collision axis by studying hard probe production as a function of impact parameter [14].

At the LHC the nuclear parton distributions will be probed at much lower x and higher Q^2 than at RHIC. This added reach is critical for exploring the kinematic region where the partons overlap and where the interesting saturation effects can be observed.

The *post-collision* environment can be studied with hard probes which undergo strong final state interactions. Such probes are high- p_T quark and gluon jets, the hadronic decays of W^\pm and Z^0 bosons, and heavy quarkonia. Due to their hard production scales, they materialize very early after the collision and are thus embedded into and propagate through the dense environment of softer secondary particles as it forms and evolves. Through their interactions with these particles they measure the properties of the evolving medium and are sensitive to the formation of a quark-gluon plasma. Large transverse momentum probes are easily isolated experimentally from the background of soft particles produced in the collision. The high p_T of the probes ensures that the medium effects are perturbatively calculable which strengthens their usefulness as quantitative diagnostic tools. At the LHC the production rates for jets with $p_T > 50$ GeV are several orders of magnitude larger than at RHIC, allowing for systematic studies with high statistics in clean kinematic regions, far beyond where the RHIC experiments reach their limits.

Quark jets of known energy can be produced in reactions such as $g + q \rightarrow q + \gamma$ or $g + q \rightarrow q + Z^0$. At the LHC, Z^0 +jet final states become measurable and may provide a more distinctive signature because the Z^0 is free from the high background of hadronic decays contributing to the direct photon spectrum [15]. The initial energy of the quark jet can be inferred from the measured momentum of the Z^0 or photon. Any energy loss of the jet suffered by interactions with the hot medium can thus be cleanly identified [16]. The measured energy loss yields the opacity of the medium, i.e. the product of the cross section between the hard probe and the partons in the medium and their density [11, 12]. In kinematic regions where the rescattering cross section can be reliably calculated, the opacity provides access to the parton density after the collision and allows one to determine how it is affected by gluon saturation. Similar information can be extracted from a measurement of the ratio of monojet to dijet final states [17, 18]. At the LHC, both types of measurements will be observable

over a wide kinematic range, thus allowing studies of the energy loss as a function of jet p_T .

Heavy quarkonia also provide sensitive probes of the parton densities after the collision. In a dense medium, the formation of charmonium and bottomonium states is inhibited since the medium screens the interaction between the heavy quark and antiquark. Different resonances “melt” at different temperatures, such that they act as a “thermometer” to probe the temperature attained in the collision. Systematic measurement of many different quarkonium states, including the dependence of the suppression effect on their transverse momenta, are required to fully understand the system [19, 20]. At RHIC, investigation of the Υ system will be severely limited by statistics while at the LHC both $c\bar{c}$ and $b\bar{b}$ resonances can be studied in detail. It has been argued that the interpretation of Υ suppression data is cleaner than for the J/ψ due to reduced rescattering effects with hadrons during the late collision stages, a further point in favor of studying heavy quarkonia at the LHC where the Υ family is comfortably accessible. Finally, we note that at the LHC secondary J/ψ production from $B \rightarrow J/\psi + X$ becomes relevant. Since B mesons are sensitive to the energy loss of b quarks [21], these secondary J/ψ mesons can be used as a further probe of jet quenching [22].

Higher production cross sections at the LHC also favorably affect the study of physics issues which are accessible in peripheral nuclear collisions where the two nuclei do not overlap. Multiple vector meson production will be greatly increased [23]. Photoproduction of top quarks in peripheral collisions becomes possible and probes the nuclear gluon distribution function at high Q^2 [24]. Finally, photoproduction of $c\bar{c}$ and $b\bar{b}$ will provide an alternate method for measuring the low- x gluon distribution [25].

We have stressed those aspects of heavy-ion physics at the LHC which are unique or qualitatively different from RHIC. In addition to these, experiments at the LHC will also study soft probes, building on what has been done at RHIC. The increased energy will extend measurements of excitation functions far beyond RHIC data, thus providing a significant additional lever arm. The increased final multiplicity densities will allow for improved measurements of many soft physics observables which require high statistics, especially event-by-event fluctuations and correlation measurements.

3. General Perspective. Size and scope of the proposed effort.

The LHC is the latest in a long line of particle accelerators exploring physics at the high-energy frontier. It is a global project with contributions from five continents. Its colliding proton and heavy-ion beams will deliver the highest energies worldwide for years to come. Furthermore, it is unclear when or if there will be another even more powerful hadron collider after the LHC. The US high energy physics community has participated in all major high energy projects and is presently investing 440 million US dollars into the construction of the LHC and its particle physics experiments, thereby securing its place at the front of high energy physics research. Similarly, to study relativistic heavy-ion collisions at the frontier, the US heavy-ion community

has always made use of or constructed the latest and best facilities available. The LHC should not become the first exception.

Four large experiments, covering a rich and very exciting physics program, have been planned for the LHC. This program is broadly accepted by the scientific community at large and has been approved by all relevant CERN Committees. Detector construction is well on its way and expected to be largely complete in 2005. One of the LHC detectors, ALICE, is a dedicated heavy-ion experiment. Another experiment, CMS, has incorporated heavy-ion studies as an integral part of their scientific program. New data from heavy-ion collisions at unprecedentedly high energies will thus emerge shortly after the LHC turn-on in 2006, complementing the scientific program at RHIC. It is very important that the US be involved in *both* programs, even while RHIC, our “in house” facility, continues to be at the focus of the US heavy-ion effort. In order to fully understand the dynamics of nuclear matter under extreme conditions the entire available energy range must be spanned with a study of the phenomena in both kinematic regimes.

Due to the heavy US commitment towards RHIC, both in terms of manpower and funding resources, there can be only a moderate US involvement in the planned heavy-ion program at the LHC. However, such involvement would ensure the diversity that has always been a very strong aspect of our field. Although the LHC detector designs are already well advanced, a number of opportunities remain for a significant impact on the physics by the participation of the US heavy-ion community. At a recent workshop held in Berkeley on Dec.20, 2000, entitled “LHC-USA”, dedicated to LHC relativistic heavy-ion physics and the anticipated US participation in the program, these opportunities were examined. It was concluded that a meaningful US involvement should be at the level of about 10% of the US manpower presently involved in RHIC, and about 10 million US dollars in financial resources. This seems to be a moderate price to pay for access to this totally new physics domain, thereby securing for the US a stable place among the leading nations in relativistic heavy-ion physics.

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Agenda of the “LHC-USA” Workshop at LBL, Dec. 20, 2000:

9:00 - 9:10 Grazyna Odyniec: Welcome, organizational remarks
9:10 - 9:50 Miklos Gyulassy: “Strong (classical) and Weak (pQCD) Gluon Fields at LHC”
9:50 - 10:30 Ulrich Heinz: “ALICE Physics”

10:30 - 11:00 Coffee

11:00 - 11:30 Spencer Klein: “Quarkonia at LHC”
11:30 - 12:10 Terry Awes: “Direct Photons in PHOS Detector”
12:10 - 12:30 Tom Humanic: “Present Ohio State Univ. Involvement in ALICE”

12:30 - 1:30 Lunch

1:30 - 2:00 Bjørn Nilsen: “Cosmic Ray Measurements that Can be Done only Using ALICE”
2:00 - 2:15 Larry Pinsky: “Houston’s Potential Responsibilities within ALICE”
2:15 - 2:25 Jo Schambach: “On L3 Trigger for ALICE - Austin Involvement”
2:25 - 2:40 Bolek Wyslouch: “Alice TRD in Phobos”
2:40 - 3:10 Daniel Ferenc: “Selective Observables of Direct Photons Using Correlations”

3:10 - 3:30 coffee

3:30 - 7:00 discussion of content of the document, distribution of work, time scale ...

7:30 dinner

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